Neutrino-nucleus interactions as a probe to constrain double-beta decay predictions

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We propose to use charged-current neutrino-nucleus interactions as a probe of the many virtual transitions involved in neutrinoless double-beta decay. By performing ν and $\bar{\nu}$ interaction studies on the initial and final nucleus respectively, one can get information on the two branches involved in the double-beta decay process. The measurement of such reactions could help to further constrain double-beta decay predictions on the half-lives.

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The experimental evidence of neutrino oscillations has opened a new exciting era in neutrino physics [1]. The observation of non-zero neutrino masses and mixings is important for various domains of physics, from high-energy physics to cosmology, and has triggered many theoretical investigations as well as experimental projects. This discovery represents a big step forward in our knowledge of neutrinos properties. Still, these particles have many mysteries to unveil, one of the key open questions being the Dirac or Majorana nature of neutrinos, which is currently explored with the search for neutrinoless double-beta decay in nuclei. The observation of such a process would represent an outstanding discovery. Besides, important information on the neutrino mass scale, on the hierarchy and on the Majorana phases could be obtained (see e.g. [2]).

In the last decades important progress has been done on the double-beta decay process, both from the experimental and from the theoretical points of view [3, 4, 5, 6, 7, 8, 9]. Concerning the experimental achievements, the two-neutrino (2ν) double-beta decay process is now observed in a large ensemble of nuclei, and the half-lives for several isotopes are being measured with a very high precision [10]. As far as the neutrinoless (0ν) double-beta decay is concerned, the presently running NEMO3 experiment will reach a sensitivity of 0.2 eV in the near future [10]. The best present limit, in the range of 0.3-1.eV, comes from the germanium-based experiments [11]. In particular, a claim for the evidence of neutrinoless double-beta decay was made recently [12]. This will be confirmed or refuted by the future CUORE [13] and GERDA experiments. Various other projects are now under study to reach the tens of meV sensitivity [8, 9, 14]. From the theoretical point of view, present predictions of neutrinoless double-beta decay half-lives still exhibit important differences for the same candidate emitter. Understanding the origin of the differences in the nuclear matrix elements that determine such decay rates represents an essential step in the future, both for the search of neutrinoless double-beta decay, and to fully exploit a positive result.

So far, several related processes have been considered to constrain theoretical calculations: the charge-exchange reactions [15], β_+ and β_- decays (see e.g.[4, 16]) and muon capture [17]. Different states are probed in these processes. In charge-exchange reactions mainly information on the allowed Gamow-Teller transitions is obtained. Concerning beta-decay, only transitions to low-energy states are probed, whereas high-energy states can be excited in muon capture, which explores one of the two branches of the double-beta decay process only.

In this letter, we propose to use charged-current neutrino-nucleus interactions as a supplementary probe to constrain the calculations on the neutrinoless double-beta decay half-lives. We discuss that such processes probe the many virtual states involved. In particular, neutrino-nucleus interactions have two specific features compared to the double-beta decay related processes considered until now. If both ν and $\bar{\nu}$ beams are available, the measurement of ν ($\bar{\nu}$) interactions on the initial (final) nucleus can probe the two branches. The relevant information on the Fermi and Gamow-Teller type (also called forbidden) transitions could be gathered by varying the impinging neutrino energy, since the contribution of these states to the total cross section increases for increasing neutrino energy. We illustrate this point by taking ^{48}Ca as a typical example. Such measurements could be performed at facilities producing low-energy neutrinos, like the one proposed at SNS and exploiting conventional sources (pion and muon decay-in-flight or decay-at-rest) [18], or with a low-energy beta-beam facility [19] which uses the beta-decay of boosted radioactive ions [20]. The latter option has two particularly attractive features. First, very pure ν_e and $\bar{\nu}_e$ beams can be produced and, second, the neutrino average energy can be easily varied by modifying the acceleration of the ions (note that $E_\nu = 2\gamma Q_\beta$ where γ and Q_β are the Lorentz factor and the beta Q-value respectively). The interaction rates are discussed in [21, 22].

The transition operators involved in the neutrinoless double-beta decay are given in detail in e.g. [3, 4, 5]. These have two-body character and involve spin-isospin and isospin degrees of freedom. In the 2ν case, the energy involved is typically a few MeV, like in beta-decay. Therefore, mainly allowed Gamow-Teller transitions are involved. The measured 2ν half-lives are often used to

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constrain the calculations and, in particular, to determine the intensity of the particle-particle interaction (see e.g. the discussion in [23] and references therein). On the other hand, in the 0ν case due, for example, to a massive Majorana neutrino exchange, from the uncertainty principle one gets that the typical momentum is expected to be of the order of 100 MeV. Therefore, both Fermi and Gamow-Teller – allowed and forbidden – transitions from the initial (and final) nucleus to the intermediate one can be excited, arising from the multipole expansion of the neutrino-exchange potential (see e.g.[24]). The contribution of these states to the half-lives of various double-beta decay emitters has been explicitly shown in several works, like for the case of ^{48}Ca (see Figs. 5 and 6 of Ref. [25] and Fig.3 of Ref.[24]) and for the case of ^{76}Ge (see Figs.2 of Refs.[26, 27] and Fig.1 of [28]). In particular, Ref.[26] discusses the effect of short-range correlations on the contribution of these states. Using the multipole expansion of the neutrino potential, it is easy to show that the Fermi and Gamow-Teller type transitions are the same as the ones involved in neutrino-nucleus interactions. In fact, the general expression for the (anti)neutrino-nucleus reaction cross section can be written as [29]:

$$\sigma = \frac{G^2}{2\pi}cos^2\theta_C \sum_f p_l E_l \int_{-1}^{1} d(cos\,\theta) M_\beta, \qquad (1)$$

where $G\,cos\,\theta_C$ is the weak coupling constant, $E_l = E_\nu - E_f + E_i$ (p_l) is the outgoing lepton energy (momentum), E_f (E_i) and E_ν being the energy of the final (initial) nuclear state and the incident neutrino energy respectively and θ is the angle between the directions of the incident neutrino and the outgoing lepton. The transition matrix element M_β is given by:

$$M_\beta \equiv M_F|\langle f|\tilde{1}|i\rangle|^2 + M_{G0}\frac{1}{3}|\langle f|\tilde{\sigma}|i\rangle|^2 + M_{G2}\Lambda \qquad (2)$$

where, in particular, the squared nuclear matrix elements involve isospin and spin-isospin degrees of freedom and a generalized Bessel function as a radial part:

$$|\langle f|\tilde{1}|i\rangle|^2 = a_i \sum_l |\langle J_f\| \sum_k t_+(k)j_l(qr_k)\,Y_l(\hat{\mathbf{r}}_k)\|J_i\rangle|^2,$$
$$(3)$$

$$|\langle f|\tilde{\sigma}|i\rangle|^2 = a_i \sum_{l,K} |\langle J_f\| \sum_k t_+(k)j_l(qr_k)[Y_l(\hat{\mathbf{r}}_k)\times\sigma]^{(K)}\|J_i\rangle|^2.$$
$$(4)$$

Here, k labels the space and spin-isospin coordinates of the k-th nucleon, l, l' are the orbital angular momenta and K is the total angular momentum of the transition operators and with $a_i = 4\pi/(2J_i+1)$, $b_{l,l'} = (-1)^{l/2-l'/2+K}\sqrt{2l+1}\sqrt{2l'+1}$. The coefficients M_F, M_{G0} and M_{G2} [29] appearing in (2) depend on the momentum q transferred to the nucleus and on the standard form factors. (Note that, since neutrino-nucleus interactions are essentially a one-body process, the cross
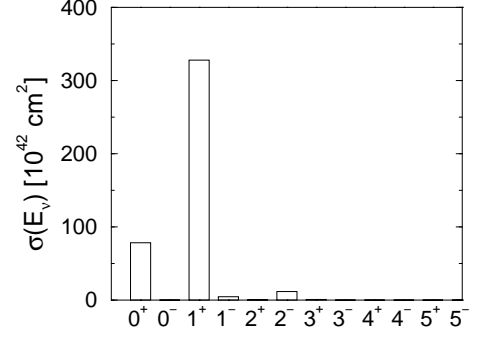

FIG. 1: Contribution of the states of different multipolarity to the total charged-current ν_e+^{48}Ca cross section for neutrino energy $E_\nu = 30$ MeV. The histograms show the contribution of the Fermi ($J^\pi = 0^+$), the Gamow-Teller (1^+) and the spin-dipole ($0^-, 1^-, 2^-$) states and all higher multipoles up to 5.
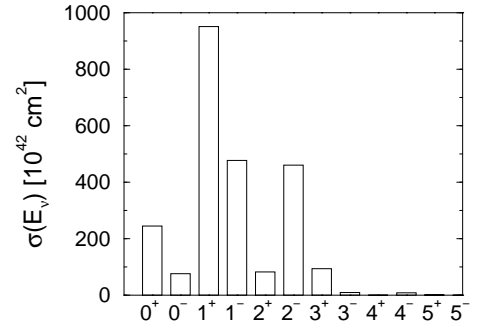

FIG. 2: Same as Fig.1 for $E_\nu = 60$ MeV.

sections are not influenced by short-range correlations.) In the limit of small momentum transfer, the operators in (3-4) reduce to the allowed Fermi and Gamow-Teller operators. On the other hand the q-dependent operators are the same as the ones involved in muon capture (except for the radial dependence which, in that case, includes the muon wave function).

The possible future availability of neutrino beams having several tens of MeV could offer the opportunity to perform neutrino-nucleus interaction studies at different energies, exploiting either the decay-at-rest or in flight of muons and pions [18], or low-energy beta-beams [19]. The relevant information on the transition matrix elements could be disentangled by varying the impinging neutrino energy since the importance of these states – relative to the allowed Fermi and Gamow-Teller ones – varies with the neutrino energy. We illustrate this feature by taking the case of ^{48}Ca as typical example. The results are obtained by using the microscopic proton-neutron Quasi-Particle Random Phase Approximation (QRPA) using Skyrme forces. The details of the approach can be found in [30]. The pairing gap is taken to reproduce experimental separation energies and the force used is SGII. Similar trends are obtained with the SIII force. Note that, as far as the double-beta decay of ^{48}Ca is concerned, several calculations exist in the literature ei-

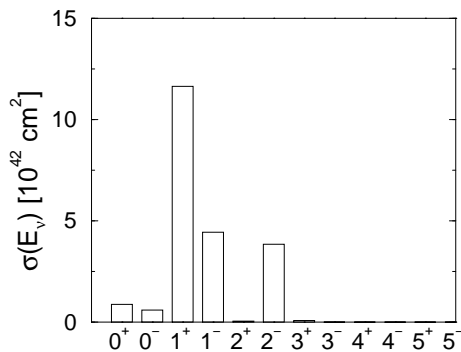FIG. 3: Same as Fig.1 for $\bar{\nu}+^{48}$Ti.

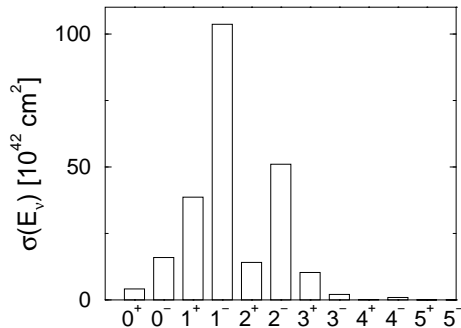FIG. 4: Same as Fig.3 for $E_\nu = 60$ MeV.

multipoles (Figure 3). The situation is quite different for $E_{\nu,\bar{\nu}} = 60$ MeV where the contribution of the spin-dipole ($J^\pi = 0^-, 1^-, 2^-$) states as well as higher multipoles (mainly the $J^\pi = 2^+$ and 3^+ in this case) becomes as important (or even dominates) the total cross section. Note that such trend can appear already at lower neutrino energies for heavier nuclei. These results indicate that neutrino beams in the 100 MeV energy range could help improving our knowledge of these states and furnish a supplementary constrain, through neutrino-nucleus measurements, on the matrix elements involved in 0ν double-beta decay.

In conclusion, the search for neutrinoless double-beta decay is a crucial issue to answer the question of the Dirac or of the Majorana nature of neutrinos. The theoretical predictions on the half-lives still suffer from important differences for the same double-beta decay emitter. So far various processes have been considered to constrain the calculations. Here we have argued that the forbidden transitions which contribute to the neutrinoless half-lives in the case, e.g. of a massive Majorana neutrino exchange, are the same as the ones involved in neutrino-nucleus interactions. We have also discussed that the information on such states might be extracted if neutrino beams with different energies are available, since their role increases for increasing neutrino energy. The study of such processes has the advantage of offering the possibility, at least in principle, to explore the two branches, through the interaction of (anti-)neutrinos from the initial (final) nucleus to the intermediate one. We have illustrated these features for a typical example. Future facilities producing low-energy neutrino beams can offer the opportunity to perform such studies. We hope that this work will trigger studies on the feasibility of such experiments.

ther within the shell model approach [3, 31] or within the QRPA approach and its variants [24, 25].

Figures 1-4 illustrates how the contribution of states of different multipolarity to the total ν_e+^{48}Ca and $\bar{\nu}_e+^{48}$Ti cross sections evolves for increasing neutrino energies, i.e. $E_{\nu,\bar{\nu}}$=30 and 60 MeV. Similar results can be obtained for other candidate double-beta decay emitters. From Figs. 1 and 3 one can see that the cross section at $E_{\nu,\bar{\nu}} = 30$ MeV are mainly dominated by the allowed Fermi and the Gamow-Teller states, even though there can be a significant contribution coming from the other

[1] S.M. Bilenky, C. Giunti, J.A. Grifols, E. Masso, Phys. Rept. 379, 69 (2003) and references therein.
[2] S.M. Bilenky, A. Faessler, F. Simkovic, Phys. Rev. **D** 70, 033003 (2004); S. Pascoli, S.T. Petcov, W. Rodejohann, Phys. Lett. B 558, 141 (2003); H.V. Klapdor-Kleingrothaus, H. Päs, A.Y. Smirnov, Phys. Rev. D 63, 073005 (2001).
[3] W.C. Haxton and G.F. Stevenson, Prog. Part. Nucl. Phys. **12**, 409 (1984).
[4] J. Suhonen and O. Civitarese, Phys. Rep. 300, 123 (1998).
[5] A. Faessler and F. Simkovic, J. Phys. G: Nucl. Part. Phys. **24**, 2139 (1998).
[6] J.D. Vergados, Phys. Atom. Nucl. **63**, 1137 (2000).
[7] H.V. Klapdor-Kleingrothaus, "Sixty years of double beta decay: from nuclear physics to beyond the standard model", Singapore: World Scientific (2001).
[8] S.R. Elliott and P. Vogel, Ann. Rev. Nucl. Part. Sci. 52, 115 (2002).
[9] S.R. Elliott and J. Engel, J. Phys. G 30, R183 (2004).
[10] X. Sarazin, Proceedings to "Neutrino 2004" [hep-ex/0412012].
[11] L. Baudis et al., Phys. Rev. Lett. **83**, 41 (1999); H.V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A 12 (2001) 147; C.E. Aalseth, Phys. Rev. D 65, (2002).
[12] H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 578, 54 (2004).
[13] The CUORE Collaboration, Nucl. Instrum. Meth. A 518, 775 (2004).
[14] Yu. Zdesenko, Rev. Mod. Phys. 74, 663 (2003).
[15] H. Akimune et al., Phys. Lett. B 394, 23 (1997); J. Bernabeu et al., IPNO/TH-88-58, FTUV-88/20.

[16] K. Muto, E. Bender and H.V. Klapdor, Z. Phys. A **334**, 177 (1989); M. Aunola, J. Suhonen, Nucl. Phys. A **602**, 133 (1996).

[17] M. Kortelainen and J. Suhonen, Phys. Atom. Nucl. 67, 1202 (2004); M. Kortelainen and J. Suhonen, Europhys. Lett. 58, 666 (2002).

[18] F.T. Avignone *et al.*, Phys. Atom. Nucl.63, 1007 (2000); see http://www.phy.ornl.gov/orland/; Y. Efremenko, private communication.

[19] C. Volpe, Jour. Phys. G **30**, L1 (2004) [hep-ph/0303222].

[20] P. Zucchelli, Phys. Lett. B **532**, 166 (2002).

[21] J. Serreau and C. Volpe, Phys. Rev. C **70**, 055502 (2004).

[22] G.C. McLaughlin, Phys. Rev. C 70, 045804 (2004)

[23] V.A. Rodin *et al.*, Phys. Rev. C **68**, 044302 (2003) and references therein.

[24] K. Muto, E. Bender and H.V. Klapdor-Kleingrothaus, Z. Phys. A **339**, 435 (1991).

[25] J. Suhonen, J. Phys. G **19**, 139 (1993).

[26] A. Bobyk, W.A. Kaminski, F. Simkovic, Phys. Rev. C 63, 051301 (2001).

[27] K. Muto, E. Bender and H.V. Klapdor-Kleingrothaus, Z. Phys. A **334**, 187 (1989).

[28] T. Tomoda and A. Faessler, Phys. Lett. B **199**, 475 (1987).

[29] T. Kuramoto, M. Fukugita, Y. Kohyama and K. Kubodera, Nucl. Phys. A 512, 711 (1990).

[30] C. Volpe *et al.*, Phys. Rev. C **62**, 015501 (2000).

[31] J. Retamosa, E. Caurier, F. Nowacki, Phys. Rev. C **51**, 371 (1995); E. Caurier, A.P. Zuker, A. Poves, Phys. Lett. B **252**, 13 (1990).